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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL MEMORANDUM X-410

EXPERIMENTAL INVESTIGATION OF PARTIAL- AND FULL-ADMISSION CHARACTERISTICS OF A TWO-STAGE VELOCITY-COMPOUNDED TURBINE*

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SUMMARY

The effect on performance of adding an impulse-type second stage to recover a portion of the kinetic energy leaving an existing single-stage supersonic turbine is presented. Also included is the effect on performance of varying the arc of admission to the two-stage turbine from full admission down to 12.5-percent admission.

At full admission, the equivalent specific-work output obtained from the two-stage turbine at design speed and pressure ratio was 41.0 Btu per pound at an overall static efficiency of 0.529. This is an approximate increase of 22 percent in turbine work output over that for the first stage alone, which at the same conditions operated at a static efficiency of 0.433.

For the range of admissions considered, partial admission had no adverse effects on two-stage turbine performance.

INTRODUCTION

In recent years there has been an increasing interest in turbines for rocket-pump drives and auxiliary-power-unit applications. Because the turbine and turbine driving fluid constitute a portion of the rocket gross weight, it is desirable to design turbines that minimize both of these weights.

One type of turbine suitable for these applications is a high-specific-work, low-flow, supersonic turbine utilizing a high pressure drop across a minimum number of stages. One such unit, a single-stage supersonic turbine with a rotor-entering relative Mach number of 2 was designed and tested at the NASA Lewis Research Center, and the results are published in reference 1. The partial-admission characteristics of this same turbine were then studied and the results published in reference 2.

*Title, Unclassified

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One of the inherent limitations of this turbine was the low static efficiency (0.414, from ref. 1) associated with the necessarily high turbine-exit kinetic-energy loss. Theoretically, a large portion of this energy could be converted into useful work by a second stage placed downstream with a corresponding increase in turbine efficiency. To investigate this potential, an impulse-type (constant-static-pressure) second stage was designed and tested. The objectives of the program were twofold: (1) to determine the effect on overall performance of adding the second stage, and (2) to determine the partial-admission characteristics of the two-stage turbine.

The turbine was tested as a single stage alone and as a two-stage turbine. In addition, the effect of the second-stage stator on the first-stage performance was determined by testing the first stage with the interstage stator and comparing the results with the single-stage performance. Finally, partial-admission characteristics of the two-stage turbine were determined by blocking the flow to the first stage and comparing the results of 12.5-, 25-, and 50-percent admission with the full-admission performance. The same range of operating conditions was covered as in references 1 and 2.

SYMBOLS

$\Delta h'$ specific work output, Btu/lb

M Mach number

p absolute pressure, lb/sq ft

U_m mean-section blade speed, ft/sec

V absolute gas velocity, ft/sec

V_j velocity corresponding to isentropic expansion from turbine-inlet total pressure to turbine-exit static pressure

w weight-flow rate, lb/sec

γ ratio of specific heats

δ ratio of inlet-air total pressure to NACA standard sea-level pressure, p_0'/p^*

ϵ — function of γ, $\frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}}\right]$

η_s — static efficiency based on static- to total-pressure ratio across turbine, p_4/p_0'

θ^* — momentum loss parameter, see ref. 3

θ_{cr} — squared ratio of critical velocity at turbine inlet to critical velocity at NACA standard air conditions at sea level, $(V_{cr,0}/V_{cr})^2$

ν — blade jet speed ratio, U_m/V_j

Subscripts:

cr — conditions at Mach number of 1.0

R — relative to rotor blade

0 — turbine inlet

1 — free-stream station between first-stage stator exit and first-stage rotor inlet

2 — free-stream station between first-stage rotor exit and second-stage stator inlet

3 — free-stream station between second-stage stator exit and second-stage rotor inlet

4 — turbine exit

Superscripts:

' — absolute total state

* — NACA standard conditions

TURBINE CONFIGURATION

The overall turbine design parameters for this investigation were the same as those given in references 1 and 2 and were as follows:

Mean-section blade speed, $U_m/\sqrt{\theta_{cr}}$, ft/sec 342
Overall pressure ratio, p_4/p_0' 0.033
Weight flow, $\epsilon w\sqrt{\theta_{cr}}/\delta$, lb/sec 0.585

The resulting blade jet speed ratio ν was 0.174 for these design conditions. Blade jet speed ratio is defined as the ratio of mean rotor blade speed to the velocity corresponding to an isentropic expansion from turbine-inlet total pressure to turbine-exit static pressure. The single-stage full-admission turbine achieved static efficiencies of 0.414 and 0.425, as reported in references 1 and 2, respectively. This slight difference is probably due to the inability to duplicate the stator throat geometry from one assembly to another.

Design of Second Stage

The second stage was designed to operate at constant static pressure, with a resulting blade jet speed ratio ν the same as that used in the single-stage turbine. The design of the second stage required a knowledge of the after-mixing velocity diagram leaving the first stage. The assumption was made that the first-stage stator performance met the design conditions initially imposed in reference 1, that is, a total-pressure ratio of 0.86. The after-mixing velocity diagram leaving the first-stage rotor was then calculated based on the actual work output at design conditions reported in reference 2. The momentum thickness parameter θ^* was then calculated at the exit of the first-stage rotor. This value of θ^* was then assumed for the exit of the second-stage stator and rotor blade rows. Second-stage velocity diagrams were then constructed to convert a portion of the kinetic energy leaving the first stage into mechanical work in the second stage with no change in the static pressure of the gas.

The after-mixing velocity diagrams together with a sketch of a typical blade channel showing the station nomenclature used are shown in figure 1. The stator and rotor blade configurations were designed to meet these conditions. Area allowance for boundary-layer growth was provided by adjusting the flare of the inner and outer walls of the stator and rotor blades. The second-stage rotor height varied from 1.06 inches at the inlet to 1.22 inches at the exit.

Table I shows the stator and rotor blade coordinates used in the fabrication process. The same coordinates were used for the hub, mean, and tip sections.

Calculations based on the design procedure resulted in a 19-percent predicted increase in design-point specific-work output of the two-stage turbine over the performance of the first stage operating alone.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

The turbine tests were conducted in the facility described in reference 1. A cradled dynamometer was used to absorb the turbine power output. A diagrammatic sketch of the turbine test section is shown in figure 2. The insets show the fairing pieces that were installed for the first-stage tests to permit uninterrupted flow downstream of each configuration for measuring purposes. Photographs of the three configurations are shown as figure 3. The first-stage stator blades (fig. 3(a)) were bolted to the casing, and only the trailing edge of one blade is shown in figures 3(b) to (d). For partial-admission testing of the two-state turbine, flow-blockage pieces were installed both upstream and downstream of the first-stage stator row. The downstream blockage piece for 12.5-percent admission can be seen in figure 3(d).

The instrumentation used to obtain overall turbine performance was essentially the same as that used in references 1 and 2. Total-pressure and -temperature measurements were taken at the turbine inlet (station 0, fig. 1), and static pressure was measured at the turbine exit (station 4, fig. 1). For the first-stage tests, static-pressure taps were installed in the fairing pieces (insets, fig. 2) approximately 1 inch downstream of each configuration to determine turbine-exit static pressure. The full-admission and 50-percent-admission weight flows were measured with a calibrated ASME orifice. However, at the low arcs of admission the orifice was unable to measure the flow accurately. Therefore, the values of weight flow for use in calculations were obtained in the following manner: All throat areas were measured and indexed; then, for a given percentage of admission, the ratio of the combined areas of the unblocked nozzles to the total nozzle area was obtained, and this portion of the full-admission weight flow was used as the partial-admission weight flow.

All tests were conducted at the following nominal inlet conditions: a pressure of 75 pounds per square inch absolute, a temperature of 200° F, and constant speeds of 20, 40, 60, 80, and 100 percent of design speed. For each speed investigated, a range of static- to total-pressure ratios across the turbine p_4/p_0' was set from approximately 0.3 to the minimum that could be obtained, which was about 0.025.

Performance data were obtained for the three turbine configurations at full admission. Two-stage partial-admission performance data were then taken by blocking the flow to the first stage in steps of 12.5-, 25-, and 50-percent arcs of admission.

RESULTS AND DISCUSSION

Full-Admission Performance

<u>One stage</u>. - The performance of the first stage alone and with the second-stage stator in place is shown in figure 4 where turbine work output is shown as a function of overall pressure ratio for speeds of 20, 40, and 100 percent design. At design conditions of speed and pressure ratio ($p_4/p_0' = 0.033$) the first-stage turbine specific-work output was 33.4 Btu per pound. It is noted from the figure that the second-stage stator limited first-stage turbine work output at design speed to a value of 32.4 Btu per pound at a pressure ratio of approximately 0.05. At design speed and pressure ratio turbine work output was reduced by approximately 3 percent, which is not considered a severe penalty. At off-design conditions of speed and pressure ratio, the curves show consistent agreement.

<u>Two stages</u>. - The performance of the two-stage turbine is shown in figure 5 where turbine work output is again shown as a function of overall pressure ratio for both the first stage alone and the complete two stages at speeds of 20, 40, and 100 percent design. At design conditions of speed and pressure ratio, two-stage turbine work output was 41.0 Btu per pound. This represents an increase in work of about 22 percent over the first stage alone, which can be compared with the anticipated increase of 19 percent indicated by the design. This difference is attributed to smaller losses in the second stage than predicted. It is noted from figure 5 that the maximum specific-work output for the two-stage turbine was 42.4 Btu per pound, which represents an approximate 26-percent increase over the maximum obtained from the first stage alone.

The variation in static efficiency for the two turbine configurations is shown in figure 6 as a function of overall pressure ratio at design speed only. At design conditions of speed and pressure ratio, the figure indicates static efficiencies of 0.529 and 0.433 for the two-stage turbine and the first stage, respectively. This is a difference in efficiency of about 10 points, or 22 percent.

The maximum static efficiency obtained from the two-stage turbine is seen to be 0.531, as compared with 0.420 for the single-stage turbine at the same pressure ratio (0.027). The maximum efficiency of the first stage is noted to be 0.479 at an off-design pressure ratio of about 0.11 and matches the efficiency of the two-stage turbine.

A comparison is made of the single- and two-stage turbine efficiencies on the basis of blade jet speed ratio in figure 7. The bulk data points are shown for 100 and 40 percent of design speed only for clarity. A few points are shown for 20, 60, and 80 percent of design speed to define the correlation curves. This figure shows the rapid deterioration

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in performance for this type of turbine (supersonic) at off-design conditions of pressure ratio, as noted by the sharp drop from the correlation curve as ν is increased. This results from the high losses associated with the system of oblique shocks that pass through the supersonic channels at off-design pressure ratios, as discussed in reference 1.

Two-Stage Partial-Admission Performance

The results of the investigation of the partial-admission effects on the two-stage turbine performance are presented in figures 8 and 9. In figure 8, specific-work output is shown as a function of overall pressure ratio and arc of admission for 20, 40, 60, and 100 percent of design speed. No significant penalty in performance was observed as a result of partial admission for the range of admissions considered (12.5 to 100 percent). In fact, it is noted that an improvement in performance apparently exists at lower than design speeds as the arc of admission was decreased. The most significant increase was at 12.5-percent admission, where, at design pressure ratio, the specific work output increased by approximately 12 percent for 20, 40, and 60 percent of design speed. Design speed could not be obtained at 12.5-percent admission. At design speed, the performance was substantially the same for all arcs of admission, with a very slight penalty imposed by partial admission at off-design values of pressure ratio.

The variation in turbine efficiency as a function of arc of admission for design pressure ratio (0.033) is shown in figure 9 for 20, 40, 60, and 100 percent of design speed. The values of actual turbine work output required to determine efficiency were obtained from figure 8. It is noted from figure 9 that, for the range of admissions considered, partial admission had no adverse effects on design-pressure-ratio performance. In fact, at other than design speed, a slight improvement referred to previously was observed at lower arcs of admission.

SUMMARY OF RESULTS

An impulse-type second stage was placed downstream of an existing single-stage supersonic turbine to recover a portion of the high level of kinetic energy leaving the first stage and convert it into useful work. Performance data were obtained for the resulting two-stage turbine, and the results were compared with the performance of the first stage alone. Partial-admission performance characteristics of the two-stage turbine were obtained for 12.5-, 25-, and 50-percent arcs of admission. The results are summarized as follows:

1. At design conditions of speed and pressure ratio, the equivalent work output of the two-stage full-admission turbine was 41.0 Btu per

pound at an overall static efficiency of 0.529. This represents an approximate increase of 22 percent in turbine work output over the first stage alone, which at the same conditions operated at an overall static efficiency of 0.433.

2. For the range of admissions considered, no adverse effects on two-stage turbine performance were noted as a result of partial admission.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 2, 1960

REFERENCES

1. Moffitt, Thomas P.: Design and Experimental Investigation of a Single-Stage Turbine with a Rotor Entering Relative Mach Number of 2. NACA RM E58F20a, 1958.

2. Moffitt, Thomas P., and Klag, Frederick W., Jr.: Experimental Investigation of the Partial-Admission Performance Characteristics of a Single-Stage Mach 2 Supersonic Turbine. NASA TM X-80, 1959.

3. Stewart, Warner L.: Analysis of Two-Dimensional Compressible-Flow Loss Characteristics Downstream of Turbomachine Blade Rows in Terms of Basic Boundary-Layer Characteristics. NACA TN 3515, 1955.

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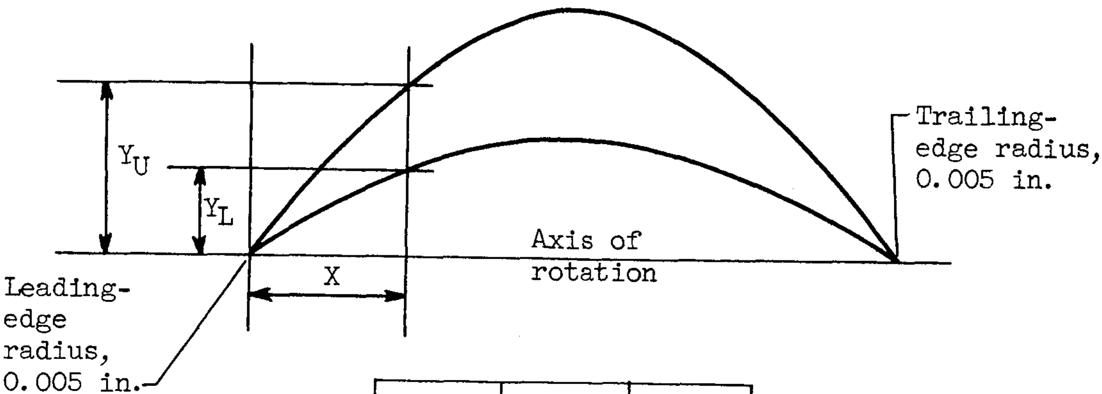
TABLE I. - STATOR AND ROTOR BLADE SECTION COORDINATES

FOR SECOND STAGE

(a) Stator



X, in.	Y_L, in.	Y_U, in.
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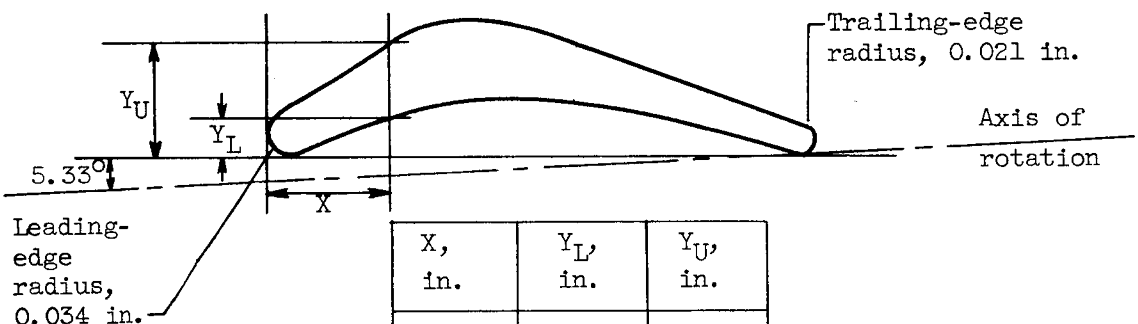
.050	.032	.064
.100	.063	.119
.150	.089	.175
.200	.110	.223
.250	.126	.261
.300	.138	.289
.350	.146	.307
.400	.149	.315
.418	.150	.316
.436	.149	.315
.486	.146	.307
.536	.138	.289
.586	.126	.261
.636	.110	.223
.686	.089	.175
.736	.063	.119
.786	.032	.064
.836	.005	.005

[redacted]

TABLE I. - CONCLUDED. STATOR AND ROTOR BLADE SECTION

COORDINATES FOR SECOND STAGE

(b) Rotor



X, in.	Y_L, in.	Y_U, in.
0	-----	0.034
.034	0	-----
.050	.004	.083
.100	.028	.114
.150	.047	.145
.200	.063	.175
.250	.075	.194
.300	.082	.198
.350	.084	.191
.400	.081	.174
.450	.076	.155
.500	.068	.136
.550	.057	.118
.600	.044	.099
.650	.030	.080
.700	.014	.061
.747	0	----
.768	-----	.021

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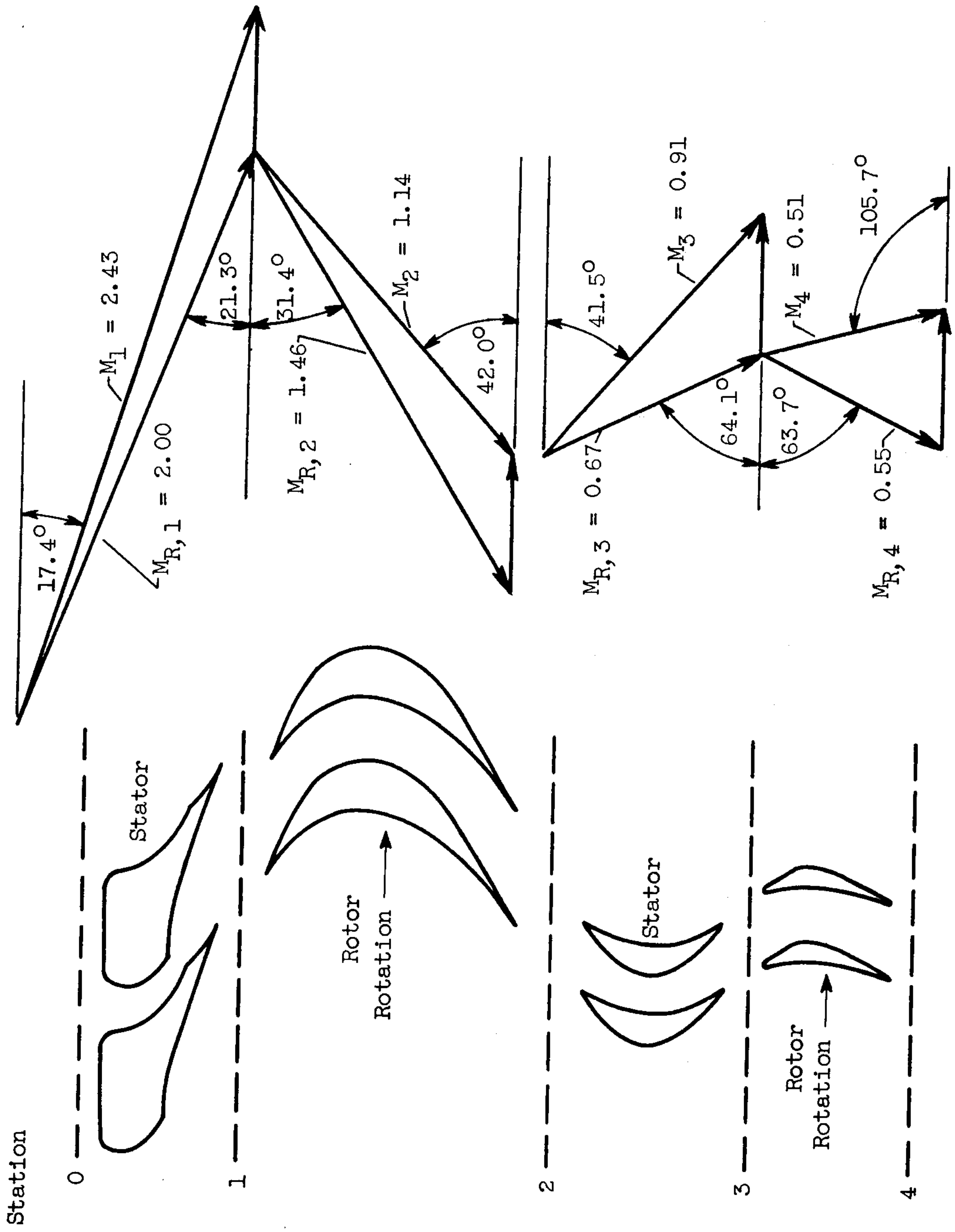

Figure 1. - Design velocity diagrams.

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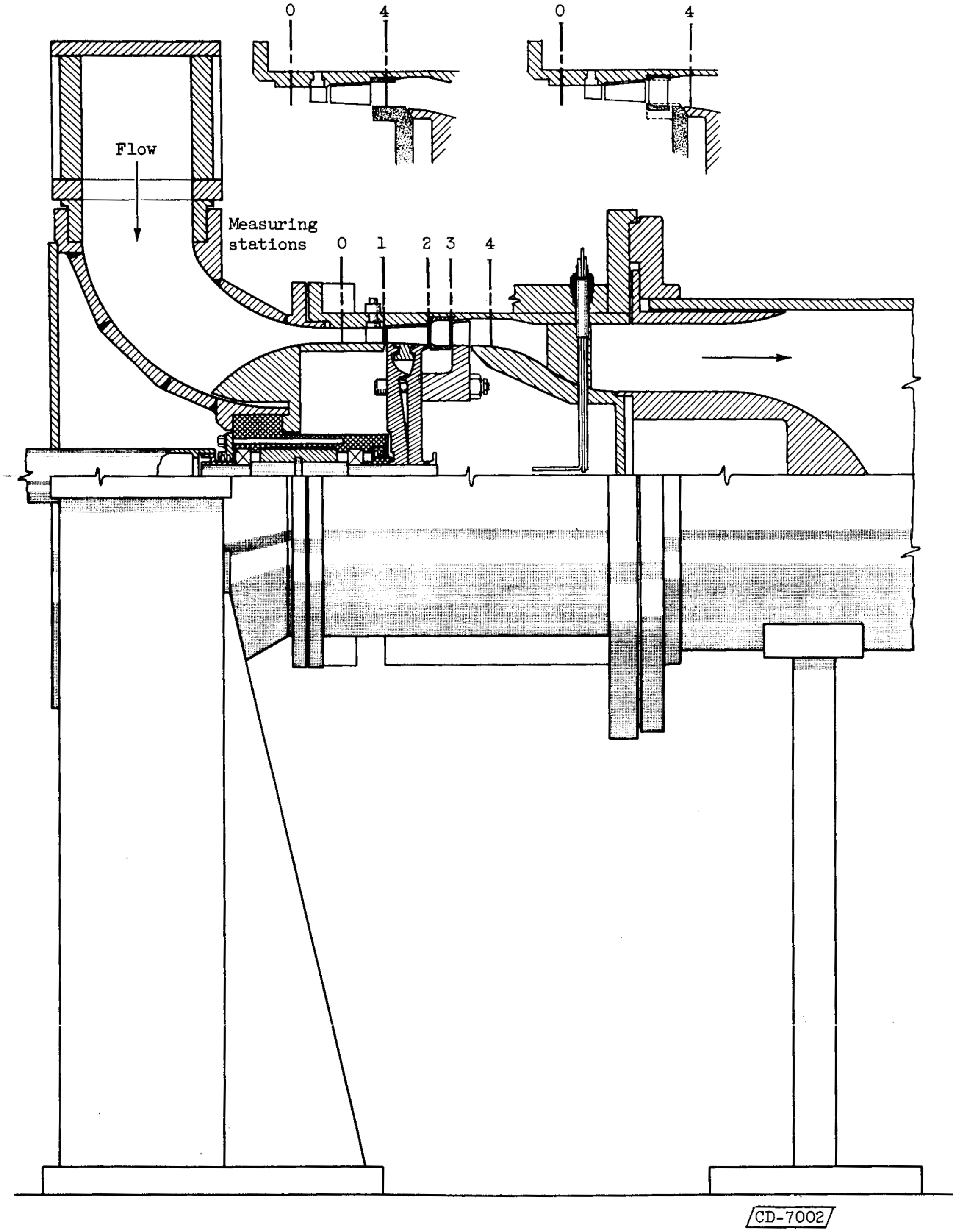

Figure 2. - Diagrammatic sketch of turbine test section.

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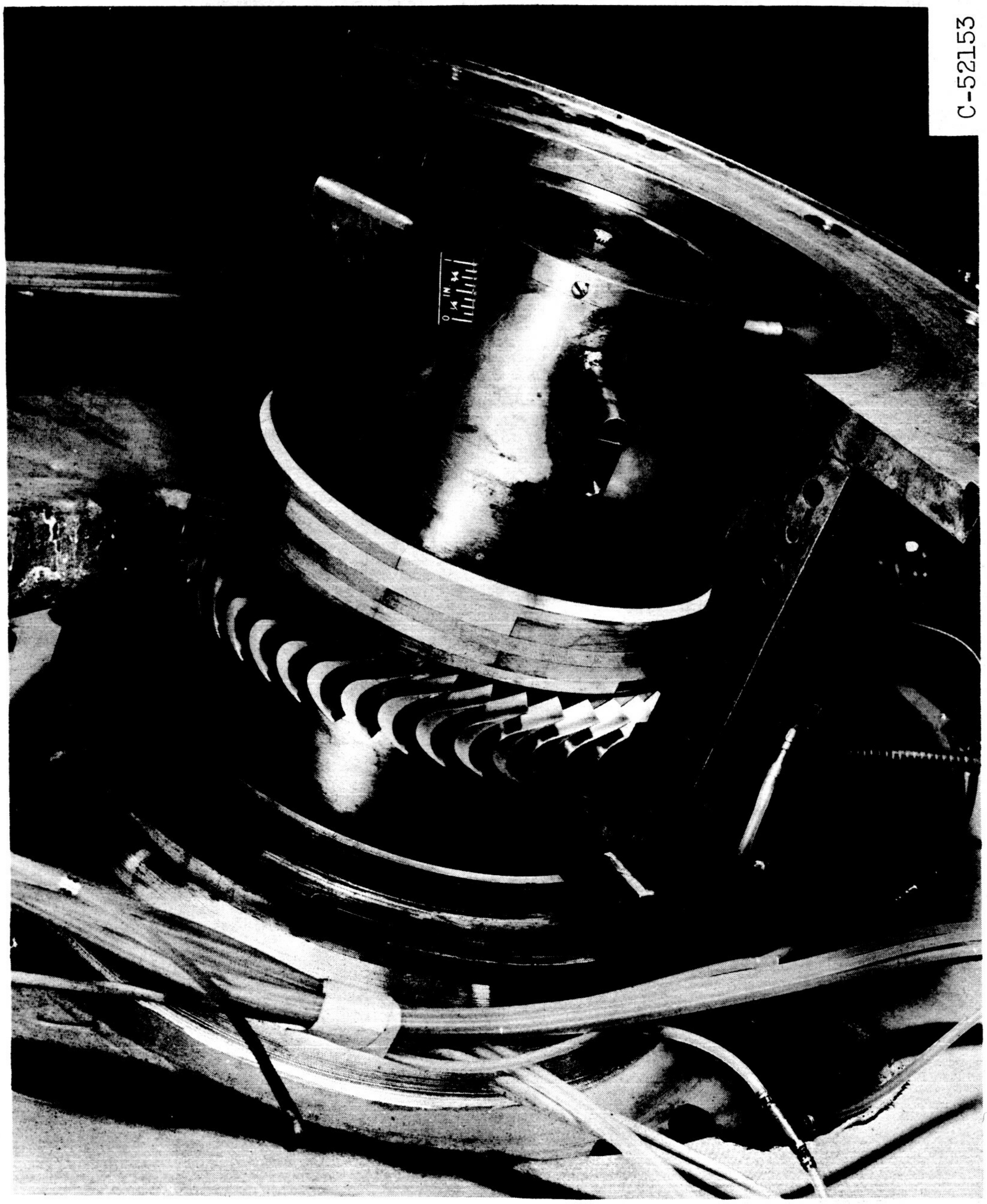
(a) First-stage stator.

Figure 3. - Turbine configurations.



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(b) First stage alone.

Figure 3. - Continued. Turbine configurations.

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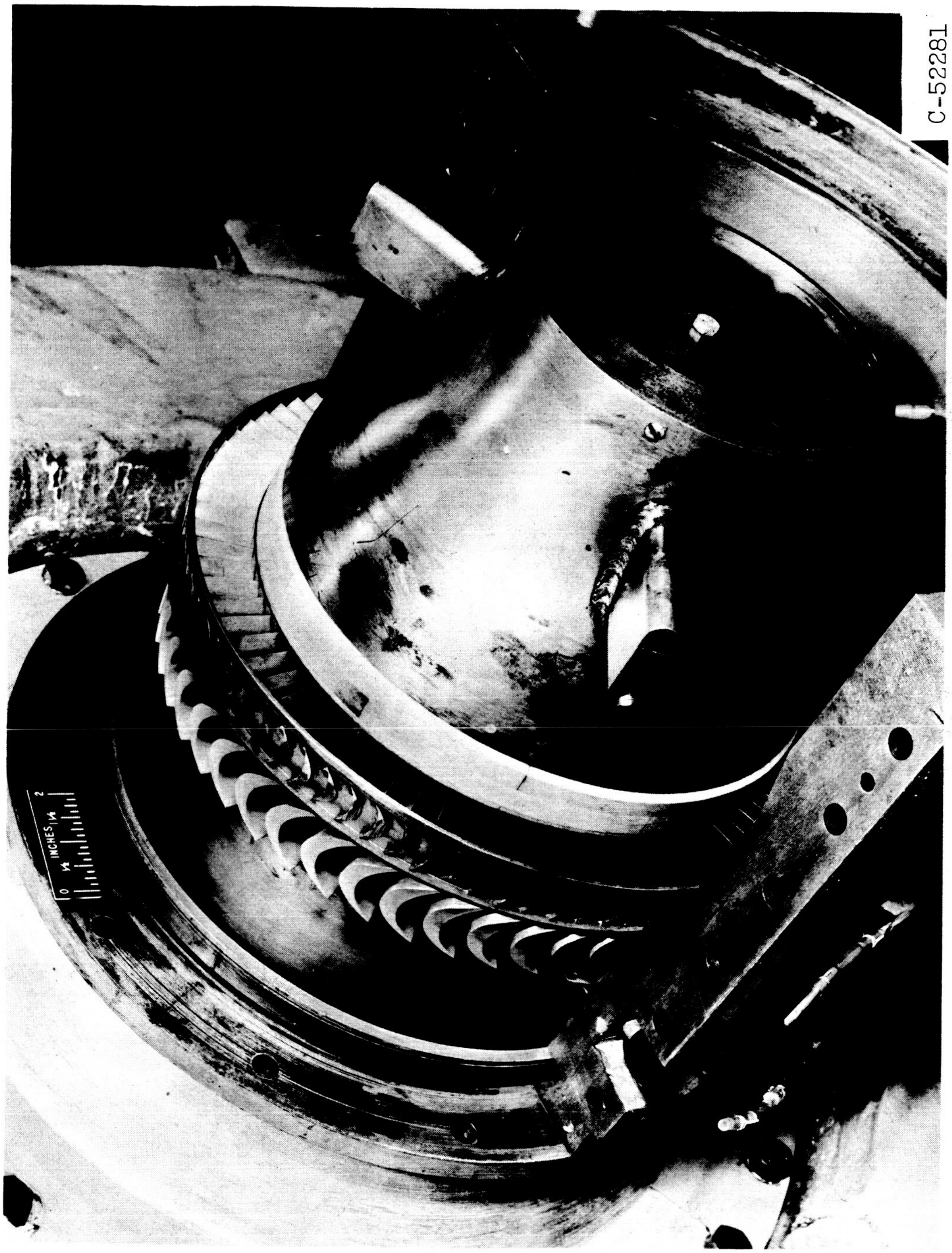

(c) First stage with second-stage stators.

Figure 3. - Continued. Turbine configurations.

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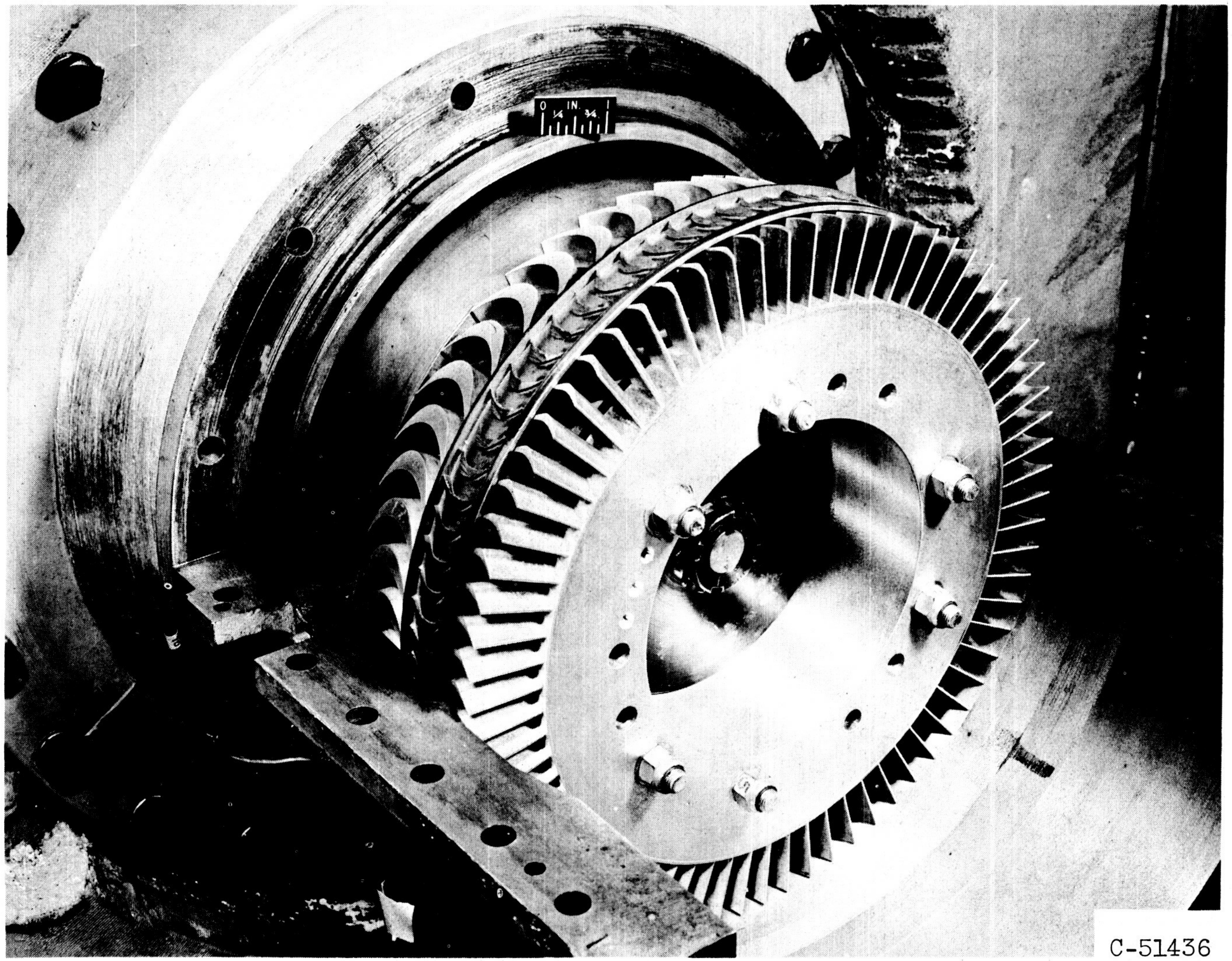

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(d) Two-stage turbine.

Figure 3. - Concluded. Turbine configurations.

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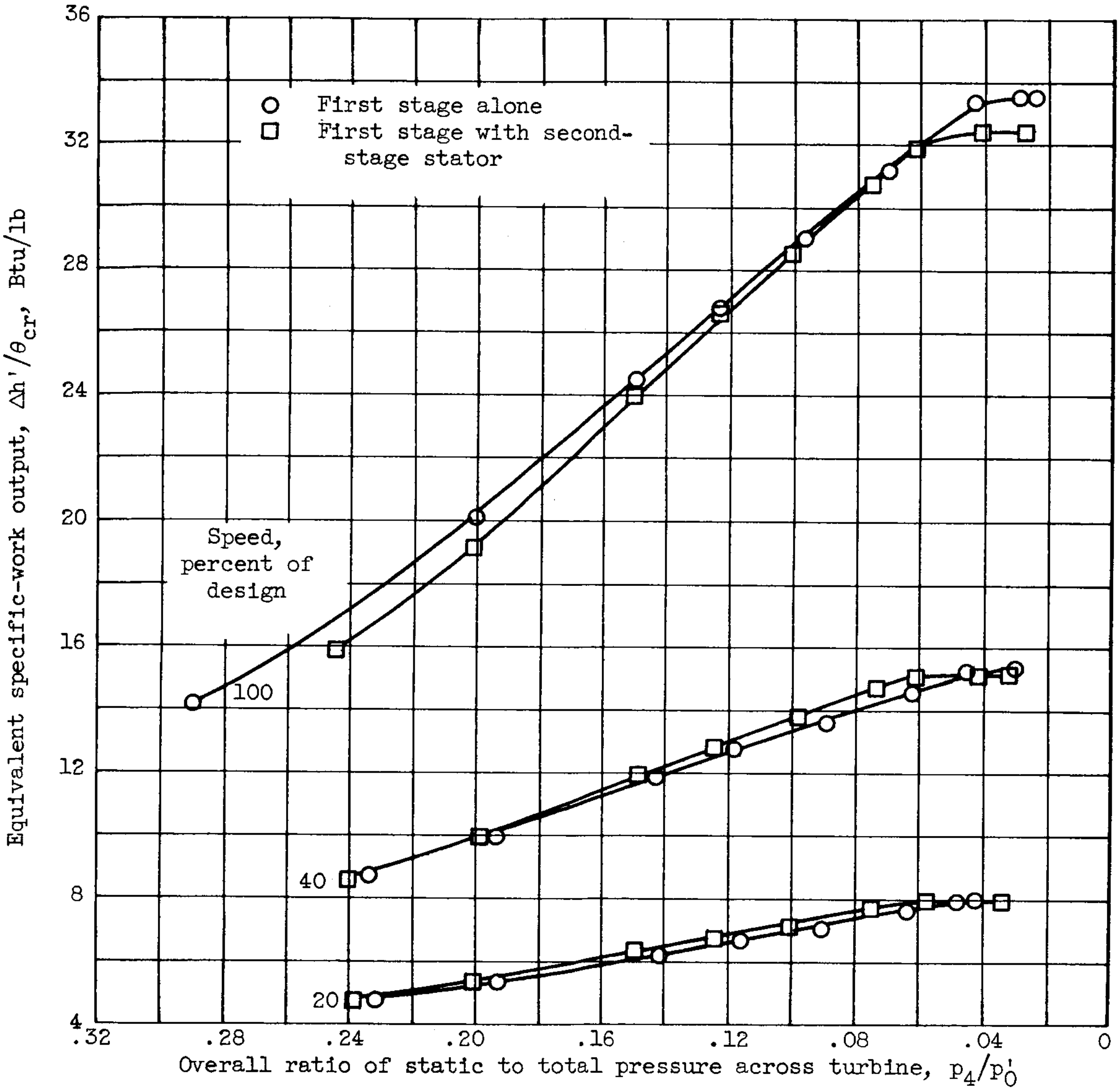

Figure 4. - Performance of first stage with and without second-stage stator.

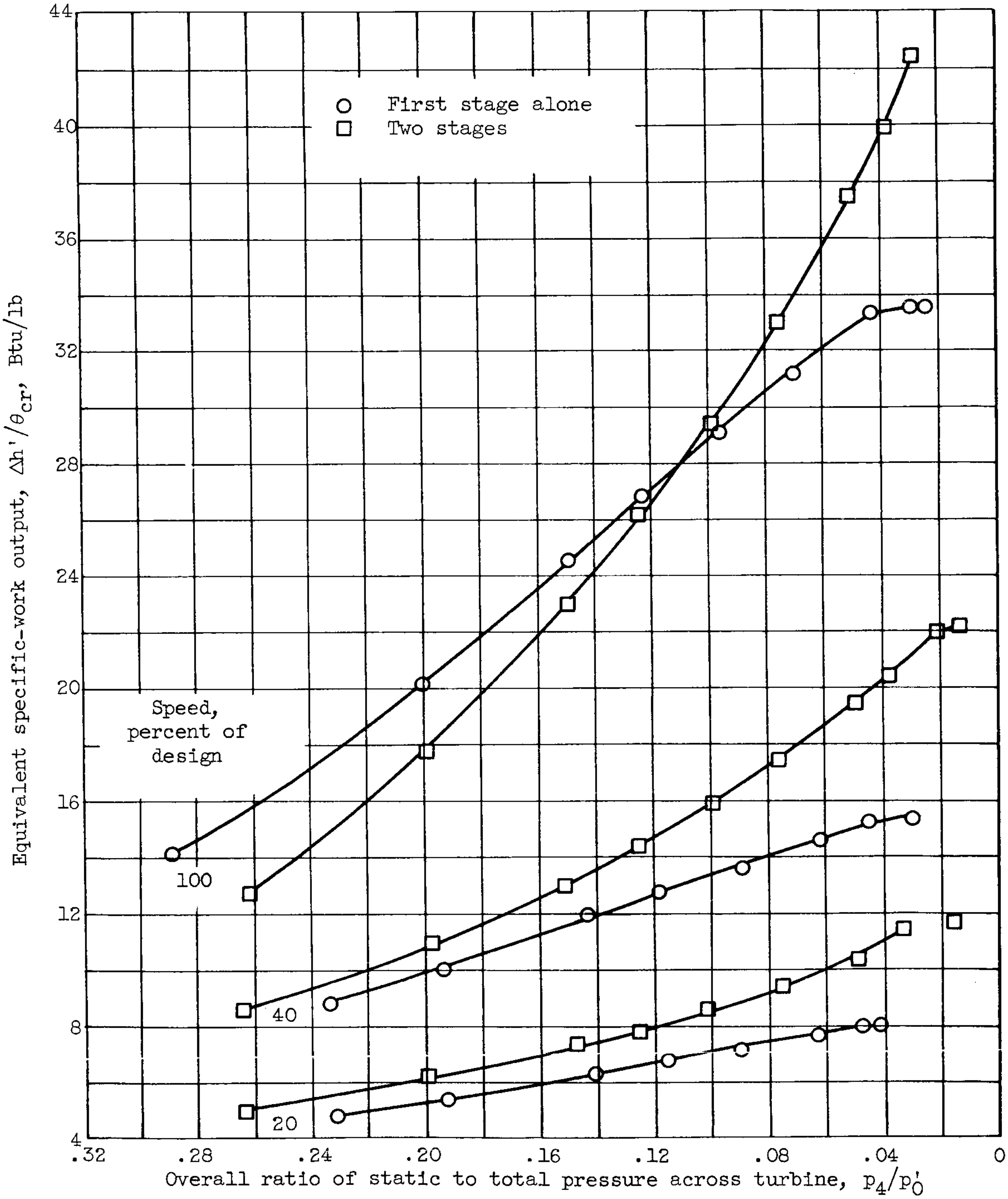

Figure 5. - Full-admission performance of first stage alone and two-stage turbine.

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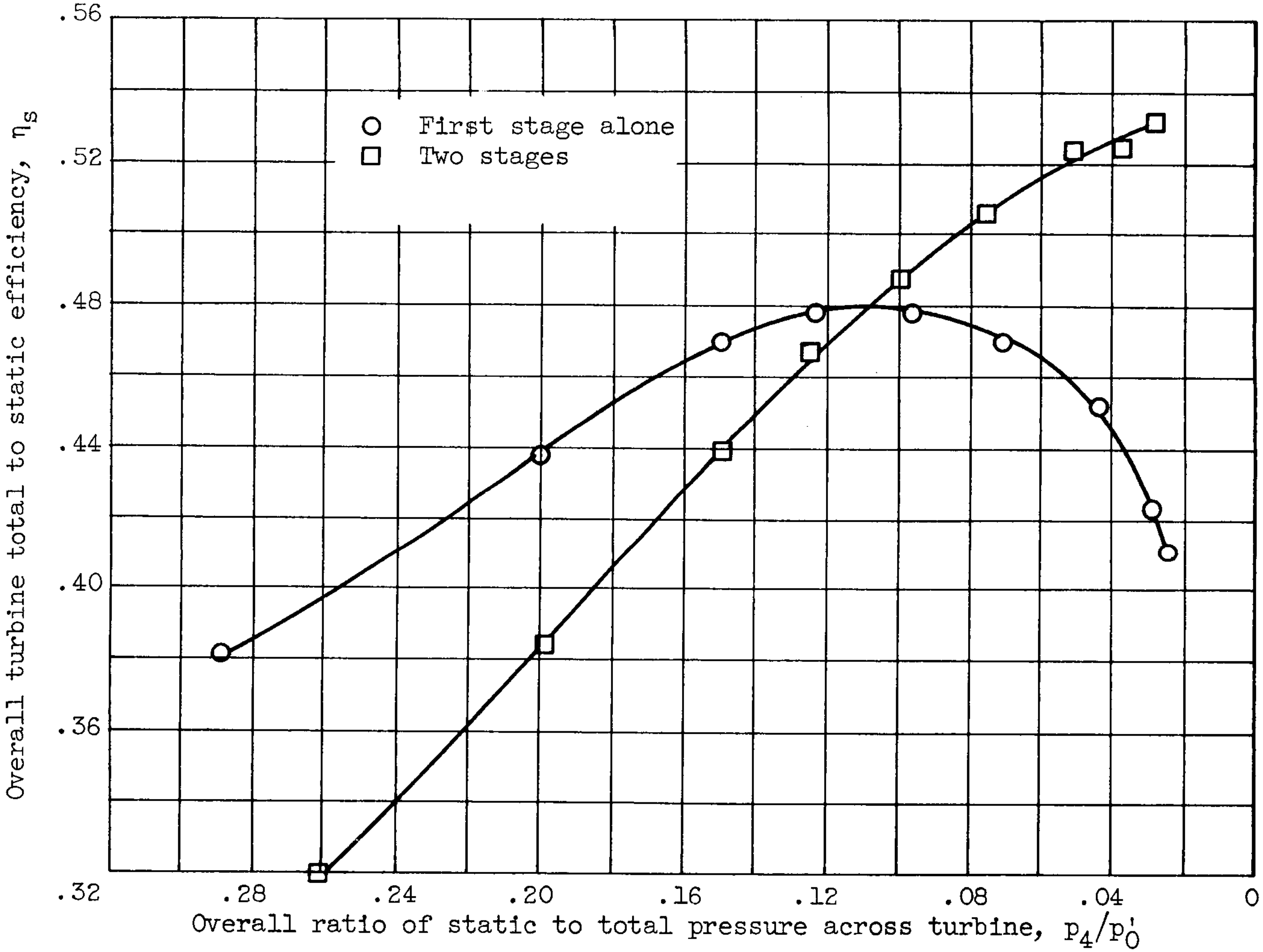

Figure 6. - Full-admission efficiency characteristics of first stage alone and two-stage turbine at design speed.

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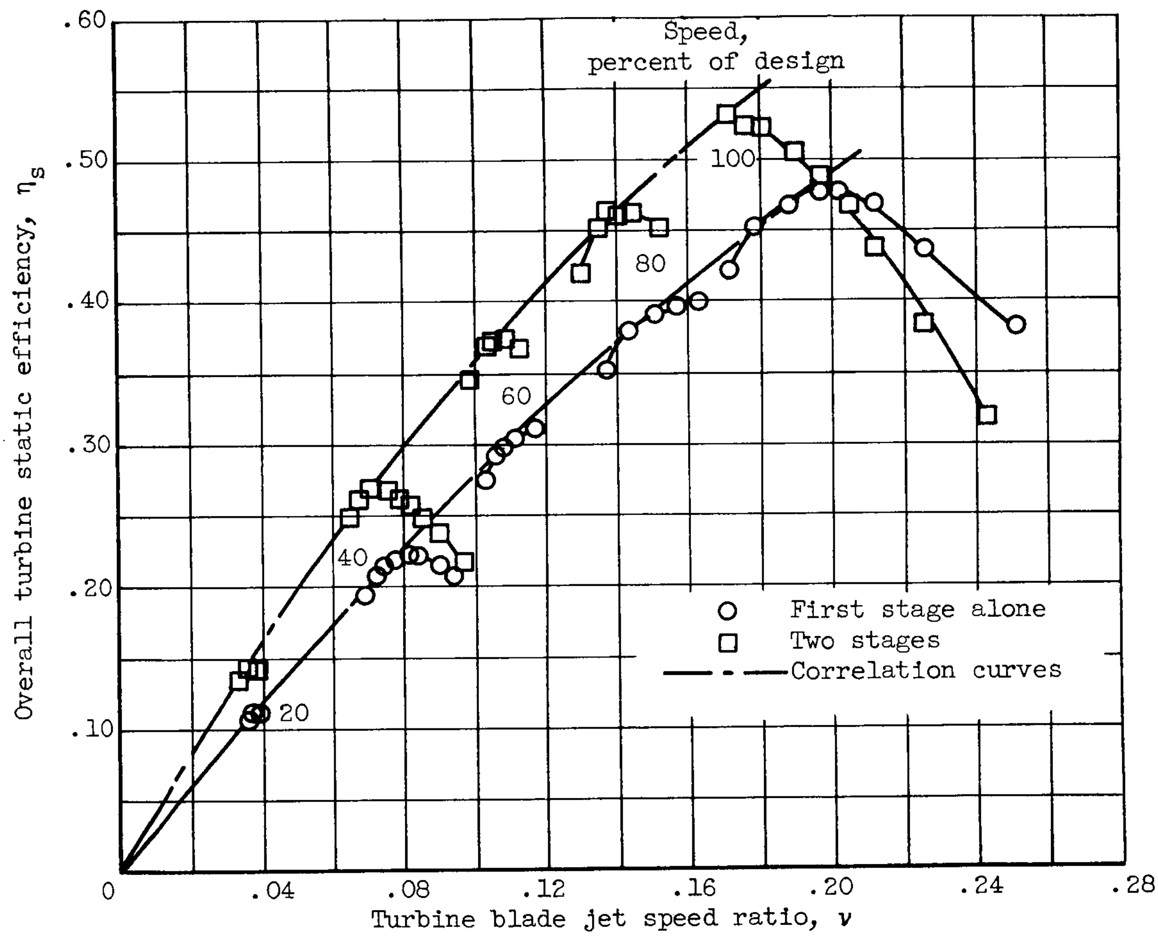

Figure 7. - Full-admission efficiency characteristics of first stage alone and two-stage turbine as function of blade jet speed ratio at design speed.

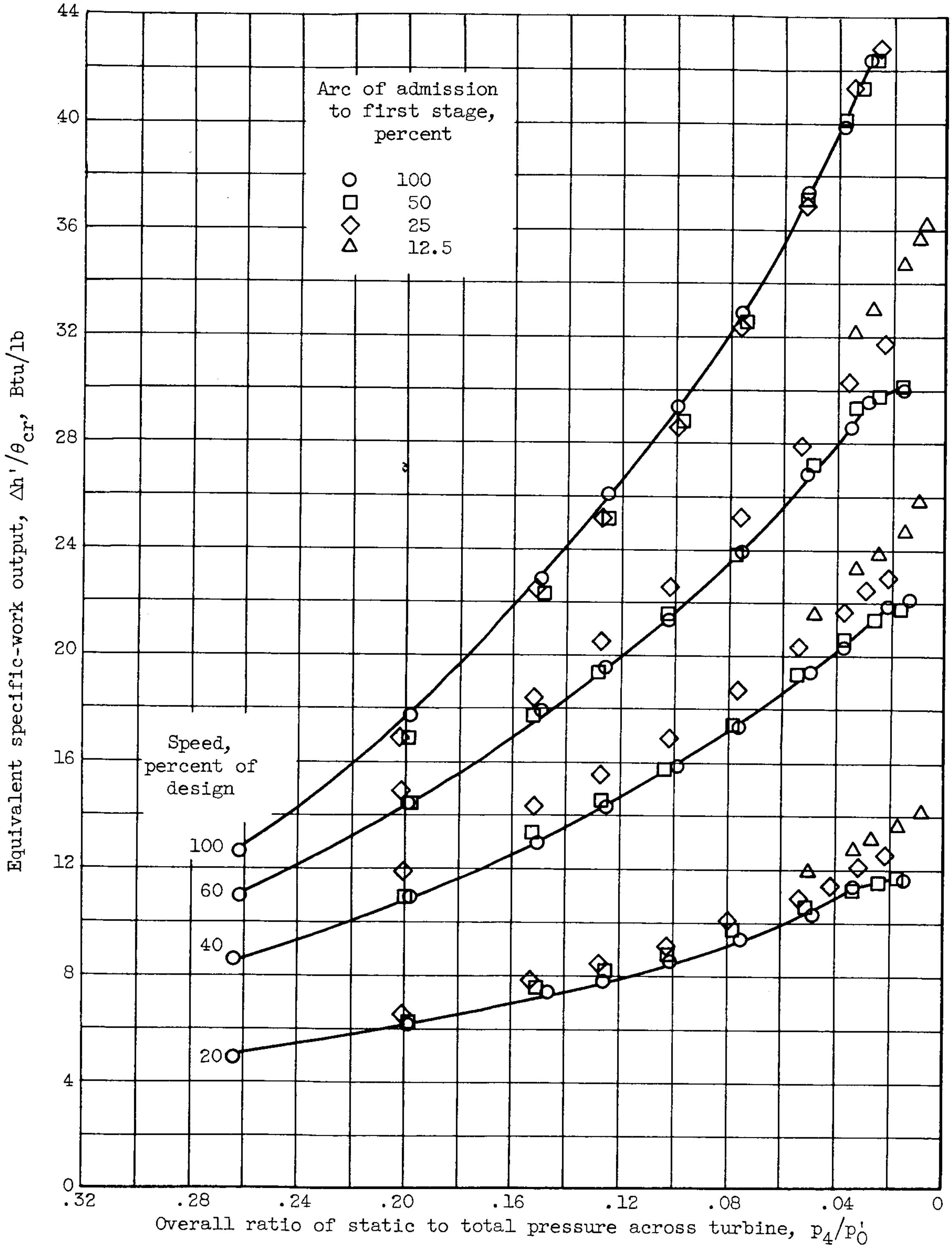

Figure 8. - Partial-admission characteristics for two-stage turbine.

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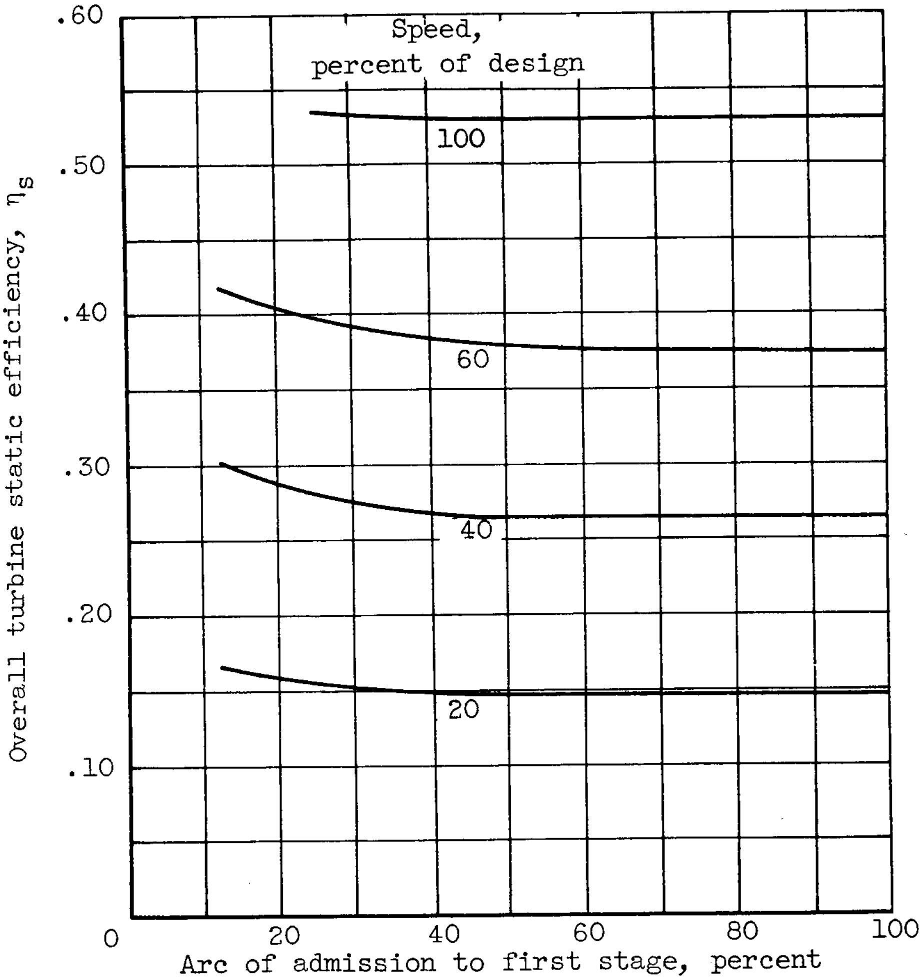

Figure 9. - Effect of partial admission on turbine overall static efficiency at design pressure ratio of 0.033.